

# Scientometric Research Progress on the Resource Utilization of Industrial Solid Waste in the Building Materials Field

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## ABSTRACT

This study adopts a scientometric approach to systematically review and critically analyze the research progress on the resource utilization of industrial solid waste in the building materials field. According to the Web of Science (WoS) database, a total of 250 relevant English papers from 2001 to 2025 were ultimately obtained. Using VOSviewer for visualization of yearly publishing patterns, authors' keyword co-occurrences, and the development history of research interests. From 2021 onwards, due to the increasing rigidity of environmental supervision and strengthening of CO<sub>2</sub> reduction targets, more articles have been published in this field over time, which shows that there is an increasing focus on researching how solid waste management links with low carbon consumption building materials. Moreover, this study provides a systematic review of the main research topics in the treatment and application of typical industrial solid waste materials in the building industry, including fly ash, coal gangue, metallurgical slag, gypsum, and red mud. From a management perspective, industrial solid waste resources have helped enhance the degree of resource utilisation through the promotion of the construction of a circular economy and reducing CO<sub>2</sub> emissions. Additionally, it raises requirements for the establishment of standard systems, implementing incentive policies, improving regional cooperation mechanisms, and constructing integrated industries. Although industrial solid waste has broad application prospects in the construction industry, there are still deficiencies in its performance improvement, durability guarantee, economy, and scale constraints during use. Future research needs to pay more attention to green treatment technologies, life cycle management, and policy-industry collaboration mechanisms' building to drive industrial solid waste from a resource utilization process towards its transition to sustainable large-scale applications.

**Keywords:** Industrial solid waste; Resource utilization; Scientometric analysis; VOSviewer; Low-carbon development; Sustainable management

## INTRODUCTION

In recent years, with the continuous advancement of urbanization and industrialization, the scale of solid waste generation has expanded substantially, becoming one of the major factors constraining sustainable urban development (Guan et al., 2024; Zhang et al., 2010). China has long remained among the largest producers of industrial solid waste in the world, and the overall generation trend continues to rise. Data show that from 2010 to 2020, the amount of industrial solid waste generated in China increased from 2.24 billion tons to 3.68 billion tons, with an average annual growth rate of 5.85% (Hua et al., 2023). Despite the continuous increase in output, the comprehensive utilization rate of industrial solid waste in China is only 55.45%, mainly due to insufficient

resource utilization technologies and relatively lagging management mechanisms. Compared with developed countries, there remains considerable room for improvement, which poses higher demands on ecological environmental protection and high-quality urban development (Hua et al., 2023).

Although abundant research achievements have been reported in the field of industrial solid waste treatment and comprehensive utilization in recent years, systematic reviews from a scientometric perspective remain relatively limited. In particular, in-depth syntheses are still lacking regarding the horizontal comparison of multiple types of industrial solid waste for building material applications, as well as their industrialization characteristics and management pathways. In fact, the resource utilization of industrial solid waste in the building materials field is not only a matter of materials and processing technologies, but also an issue closely related to resource and environmental governance and industrial collaborative management. Its wider application is jointly constrained by multiple factors, including policy frameworks, standards and specifications, regional coordination, market acceptance, and cost-effectiveness.

Based on this background, the aim of this paper is to conduct a scientometric analysis of the research development situation for industrial solid waste treatment and renewable materials technology in China's construction industry. Five typical kinds of industrial solid wastes, including fly ash, coal gangue, metallurgical slag, gypsum and red mud, were chosen for study in this paper. Their basic features, main application paths and industrial development situation were studied to provide an object of reference for the utilisation resources, value-added applications, and further harmless treatment of industrial solid wastes. Also offer some implications for relevant policies making or management practices.

## METHODOLOGY

The visualisation tool based on the scientific-technology analysis programme VOSviewer runs in the Java environment, which shows good applications of bibliometric maps and knowledge structures with its support (Van Eck & Waltman, 2010). Given that it has strong functions in finding research hotspots and analysing knowledge links, VOSviewer 1.6.20 was chosen for systematic examination of related academic papers focusing on resources utilisation across industrial solid wastes within the building materials sector. Based on this, an additional critical examination and evaluation of it were performed using scientific methodological data.

### Literature retrieval

Relevant literature has been obtained from the WoS database. The following topic search query is used during the search process: "industrial solid waste" + "building material" OR "construction material" OR "cement" OR "concrete" + utilization OR treatment. The time span for data collection was set from 2001 to 2025. In order to enhance the academic quality and representativeness of the sample literature, finally limit this study's data to formally published English journal articles and use these as sources in later scientific research methods application exploration.

### Data collection

To improve the accuracy and representativeness of the literature sample, clear inclusion and exclusion criteria were established in advance during the retrieval stage. Firstly, the search was limited to the Title Field, and the query "industrial solid waste" AND ("building materials" OR "construction materials" OR "cement" OR "concrete") AND ("utilisation" OR "treatment") was set as a basic requirement. Therefore, 300 documents were finally found. In the next stage, the language was limited to English, the document types were restricted to Article and Review Article, and the publication period was defined from 1 January 2001 to 31 December 2025. It can be seen from these records that they have been checked through the research topics during manual screening, those not relevant enough for our purpose are omitted. After all the above filtering steps have been completed, among the original 250 publications selected as candidates in the later visualisation work. As shown in Figure 1, the detailed process of literature retrieval and selection.

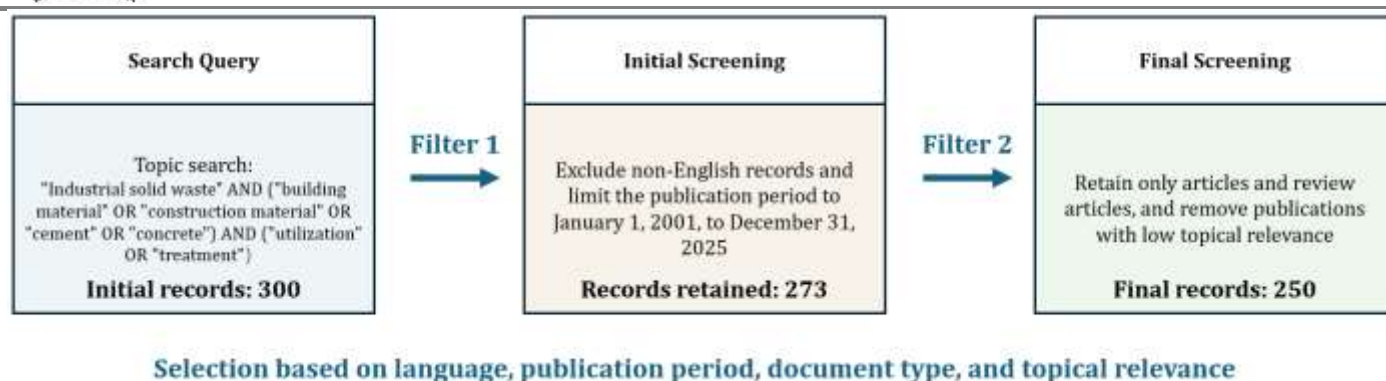


Figure 1: Flowchart of Literature Retrieval and Screening

## Scientometric Analysis

### Research trends

According to Figure 2, as a result of the initial literature screening, all publications within this time frame were ultimately included in the statistical analysis. It can be observed that only two papers were extracted in the time span of 2001-2010, as these are not closely related to the topic and have been omitted by exclusion during previous manual checks. Therefore, Figure 2 presents only the publication data from 2011 to 2025. It can be seen from 2011 to 2020 that the number of annually published works in this area has been relatively low, with slight increases. It can be inferred from this that although there was some research on treating and making full use of industrial solid waste in the building materials industry at this time, it did not become an important research topic. From 2021 onwards, the number of annual published works has significantly surged and reached a total of 20, 23, 26, 60, and 94 during this period in successive years. Among them, the number of publications in 2025 was at its peak and close to four times higher than other years; thus, it can be inferred that after several consecutive years of growth, this research theme began growing rapidly recently.

Overall, the respective curves also show a change corresponding to the changes across years of publication rates yearly. In addition, starting from 2021, the steepness of the curve is obvious, and there are especially significant increases in 2024-2025, indicating that the majority of research outputs were published within the last five years. Therefore, it can be concluded that due to increased demand for green building materials, low-CO<sub>2</sub> emission constructions and the utilisation of resources from solid waste, research on the disposal and recycling technologies for building industry wastes has become more popular over recent years. In summary, the large amount of literature produced in recent times indicates that researchers' attention to this area has been growing rapidly recently.

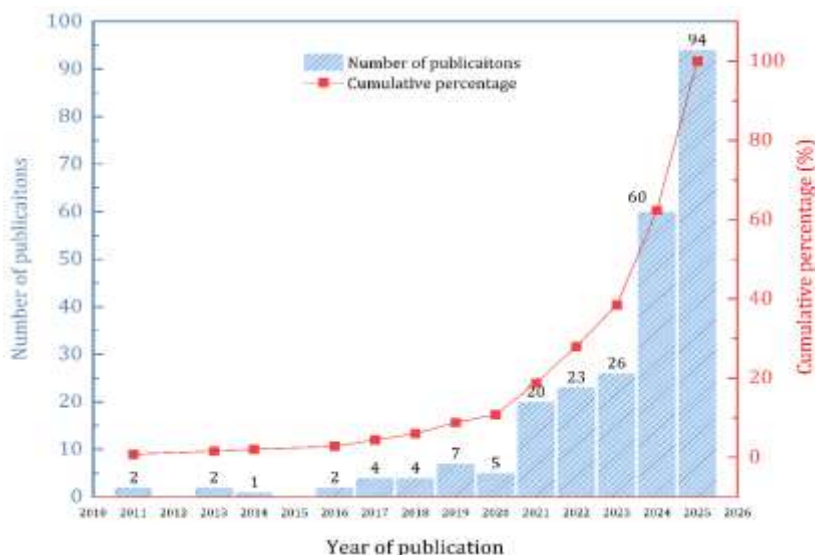


Figure 2: Annual Number and Cumulative Percentage of Publications



studying how to incorporate solid waste into traditional cement-based materials, there is now a focus on Life-Cycle-Assessment and Environmental-benefit-evaluation lines. That is to say, the proportion of scholars who are concerned with evaluating all aspects has increased compared with before. The red region is mainly composed of key words such as "microstructure", "hydrolysis" and "solidification"; Also discussed are heavy metals; These parts generally report theoretical research results about changes in Building materials due to industrial waste utilization, focusing on investigations into the effects at a microscopic level via mechanisms. The yellow group mainly consists of the following key combinations: "concrete", "coal gangue", "activity", "pozzolanic activity", "aggregate" and "emission"; It pays more attention to concrete application, the activation process and carbon dioxide emission.

Figure 4 presents the density visualization characteristics of the author keywords, in which the color transition from blue to yellow indicates the gradual increase in keyword occurrence frequency and co-occurrence density. As shown in the figure, the areas with a higher density of points are mainly around the key terms "compressive strength", "fly ash", "industrial solid waste", "cement" and "concrete", thus indicating that currently, most studies on industrial solid waste issues at present focus on mechanical properties evaluations for cement-based materials/cold base concrete systems, and amongst them, compressive strength has become the central metric being pursued across multiple fields' investigations. Keywords, such as slag, metakaolin, coal gangue, microstructure and durability, are all under these main Areas. Moreover, while keywords such as "life cycle assessment", "emission", "heavy metals" and "solidification" appear in some areas of weak density; They retain certain connections with the primary topic to varying degrees. It shows that the related research continues to expand in multiple directions, covering environmental impact assessment and sustainable development.

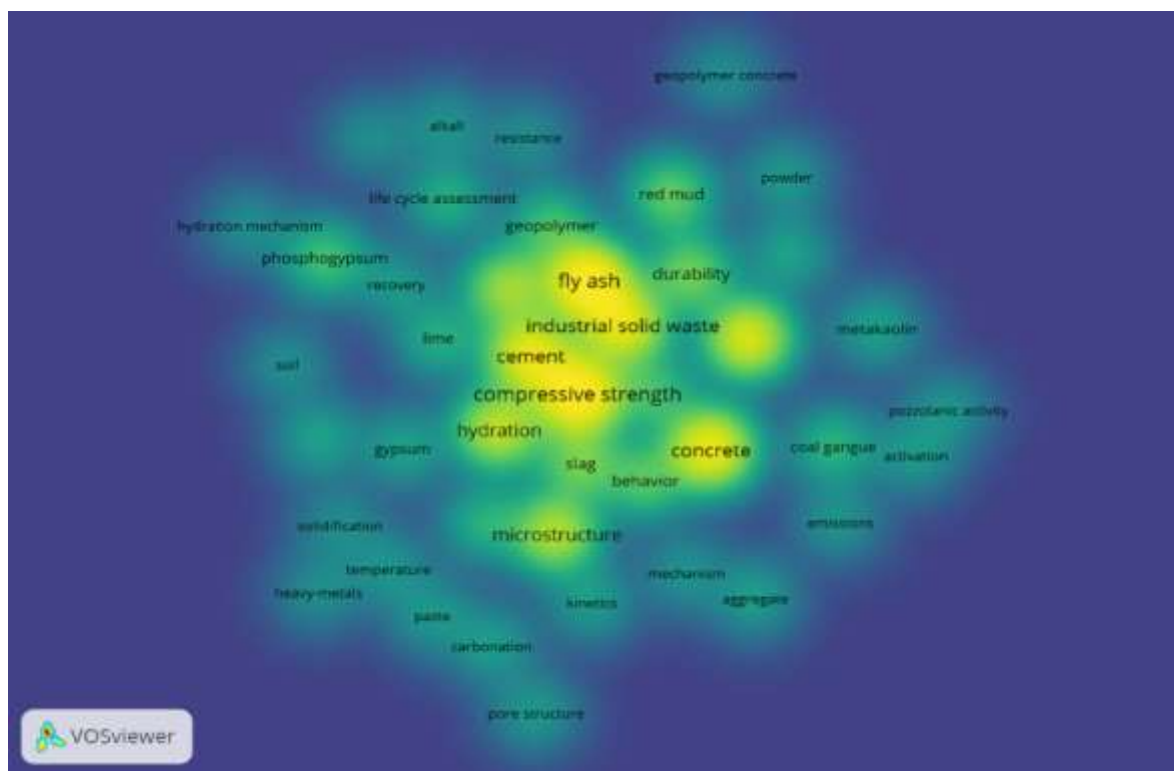


Figure 4: Keyword Density Map

As shown in Figure 5, the characteristics of the collaboration networks among the main publishing countries for this study are presented below: Nodes are sized according to their relative impact within the cooperation network; Links depict cooperative ties across different nations. To enhance the generalizability of this analysis result, the lowest number of publications required per country was three. As shown in Figure 6, out of a total of 229 papers produced by Chinese scholars, it ranked first overall among collaborating countries (with seven collaborations), demonstrating that more than half of these papers had an author from another country, including those published overseas. At the same time, China has good relations with some countries, such as the United States, Britain, Australia, Japan and Malaysia; there is also a basis for cooperation among these regions at present in this domain.



discussions are presented in detail on how to deal with and use five typical cases of industrial solid waste: Fly ash, coal gangue, metallurgical slag, gypsum, and red mud.

### Treatment and utilization of fly ash

Fly ash, as an important solid by-product generated from coal-fired power plants, not only occupies large amounts of land when stockpiled or landfilled for long periods, but may also pose persistent environmental risks due to the leaching of hazardous components. Therefore, its treatment concept has gradually shifted from conventional end-of-pipe disposal toward the coordinated goals of reduction, harmless treatment, and resource utilization (Ahmaruzzaman, 2010; Wang et al., 2020). During the treatment period, fly ash generally needs to be separated preliminarily and upgraded; especially the removal of unburnt carbon is necessary. According to several related research works so far, methods for removing unburnt carbon include: screening, gravity sorting, electrostatic sorting, flocculation and oil-gelling separation; The purpose of these techniques is not only to enhance the utilisation rates at present sites, such as building materials and functionals materials (Hower et al., 2017), but also to reduce costs (Hower et al., 2017; Xing et al., 2019).

In terms of resource utilization, fly ash has expanded from traditional bulk consumption in construction materials to value-added applications. Common applications include its use as a mineral admixture in cement and concrete, road base materials, mine backfilling materials, and low-cost adsorbents. In addition, it can also be used for the preparation of functional materials such as zeolites, mesoporous silica, and geopolymers (Ahmaruzzaman, 2010; Franus et al., 2014; Ju et al., 2023; Nayak et al., 2022). In terms of building Materials, a part replacement of Cement with fly ash may improve the fluidity of Concrete and enhance its resistance to chloride ions entering, sulfate attacks, acid corrosion (Franus et al., 2014). In terms of high-value utilization, the Al content in fly ash is usually around 16%-55%, along with Si, Fe, Li, Ga and other rare earth elements, there are significant resources left unutilised. At present, the recovery rates at this time remain less than 5% (Tian et al., 2025). Furthermore, according to Ju et al. (2023), after adopting a residue-free method for processing the fly ash silicon-extraction process can achieve a higher efficiency of over 100% than before. The prepared mesoporous silica has a specific surface area as high as 663.87m<sup>2</sup>/g with a pore volume of 0.41cm<sup>3</sup>/g and an average pore diameter of 2.73nm. These results show that there is a good prospect for applying fly ash to prepare high-value-added Materials.

### Treatment and utilization of coal gangue

Coal gangue is a typical type of bulk solid waste produced by both coal mining and cleaning, the Generation process diagram shown in Figure 8. Most of its product is in the range of around 10%-15%. China's accumulated coal gangue in history exceeds 5-7 billion tonnes; It is still rising at a rate of around 350 to 800 million tonnes per year. A large amount of land has been occupied due to long-term storage, which may also lead to problems such as spontaneous combustion and acidic wastewater discharge after decomposing (Snehasree et al., 2025; Sun et al., 2025; Wang et al., 2025).

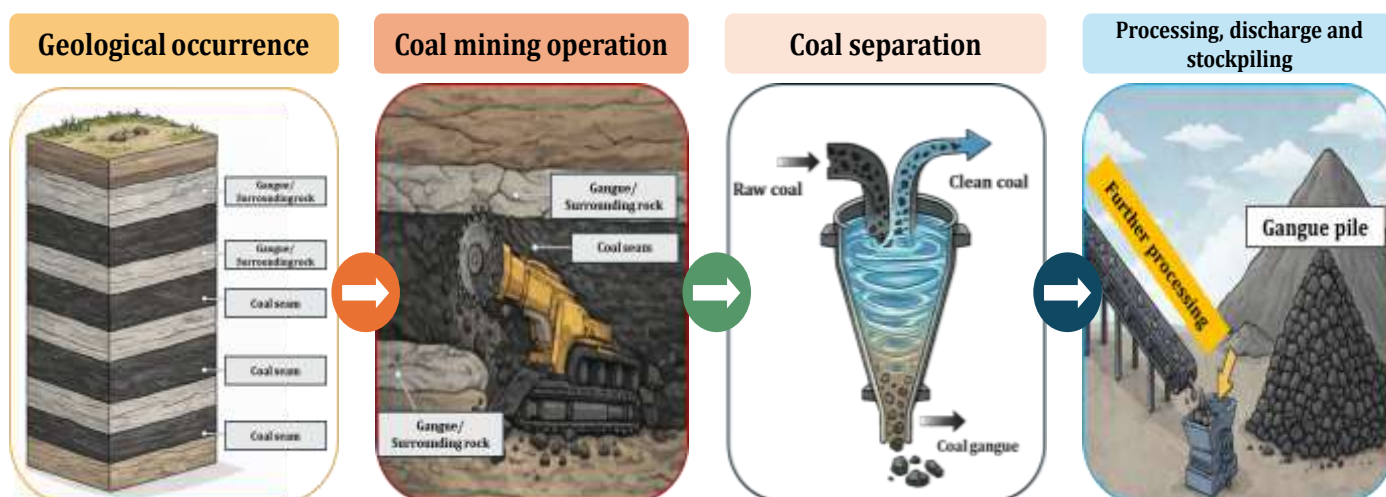


Figure 7: Coal Gangue Generation Process (Gao et al., 2024; Li & Wang, 2019)

Due to its stable crystalline structure and relatively low reactivity, the efficient utilization of coal gangue usually requires pretreatment or activation modification. As shown in Figure 7, commonly used methods include thermal activation at 500–900°C, mechanical grinding, chemical reagent activation, and microwave activation (Fei et al., 2024; Li & Wang, 2019; Wu et al., 2024). Some studies have indicated that coal gangue exhibits a relatively high content of active substances when calcined at around 650°C, while microwave calcination can achieve the transformation of kaolinite into metakaolin at 600°C, reducing the activation temperature by approximately 100°C compared with conventional methods and thereby enhancing the dissolution and reactivity of Si and Al (Chen et al., 2025; H. Liu et al., 2025).

Currently, the most widely used application fields of coal gangue include supplemental cementitious materials, geopolymer precursors and concrete aggregates due to their relatively high contents of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> (over 70%), which provide raw materials for further utilisation of coal gangue as an aluminosilicate resource (Jia et al., 2025; Wu et al., 2024). Moreover, some of it could be employed in the reutilisation of precious metals such as aluminium, iron, lithium, and gallium via thermal activation-acid leaching processes. Studies by Shao et al. (2022) and Qin et al. (2025) show that these technologies are not only used for extracting resources but also utilised in the reuse of leachate residue as soil amendment material or silicon source; thus, this kind of full-use approach has been widely promoted towards a closed-cycle system with zero emissions.

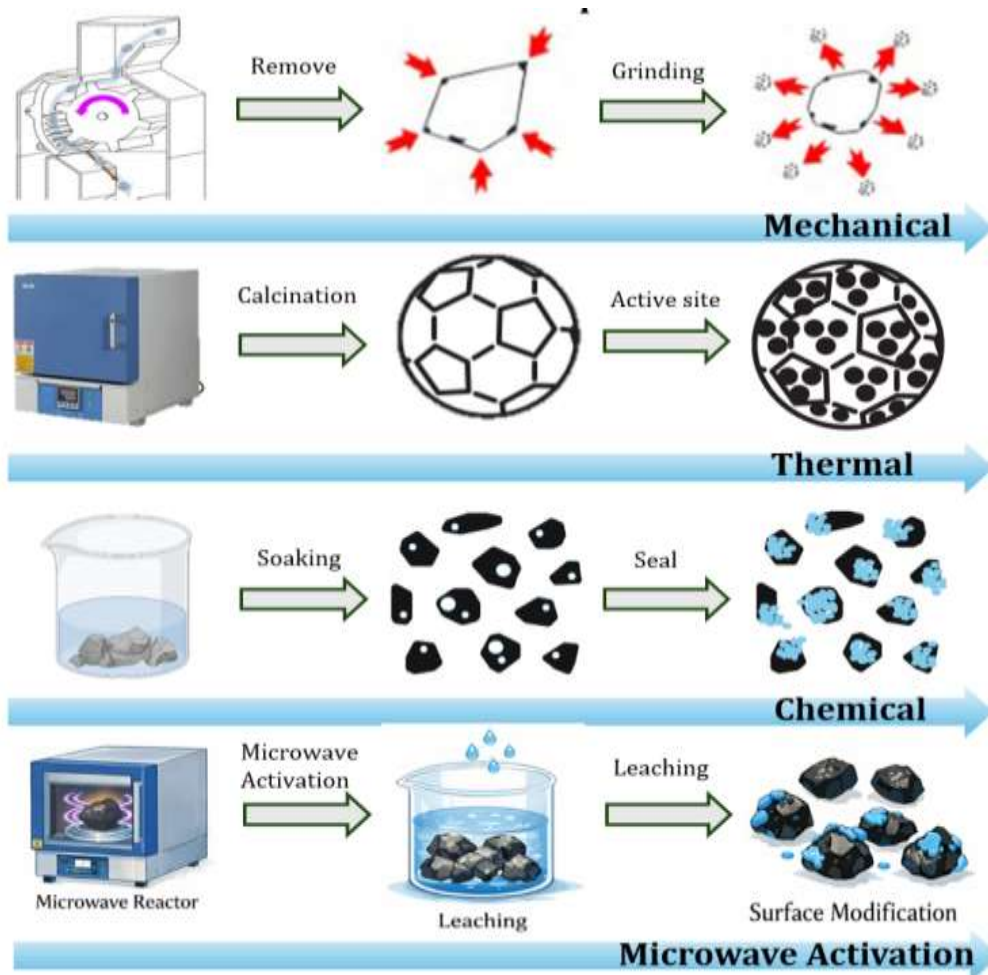


Figure 8: Coal Gangue Aggregate Modification Methods

### Treatment and utilization of metallurgical slag

Metallurgical slag includes three major categories: steel slag, blast furnace slag and other industrial wastes such as copper slag, ferronickel slag and iron-bearing smelting slag produced in the process of ferrous and non-ferrous metal refining. Such slags are generally characterized by complex compositions and large stockpiling volumes. It may lead to problems such as land occupation and heavy metal leaching pollution after a long time. Therefore, the treatment concept for metallurgical slag is moving towards both reducing its own use to some extent while

also promoting recycling as resources are reused (Gao et al., 2023; Ji et al., 2022; X. Li et al., 2024). Steel slags can be up to about 15-20% of a country's crude-steel output on average. China's annual production volume of steel slag exceeds 150 million tonnes, but the reuse rate is still much lower compared to countries like Europe and North America with well-developed industrialization (Gao et al., 2023; Yuan et al., 2024).

Metallurgical slag typically needs a pre-treatment process of ageing, heating for a long time without air, water quenching, magnetisation separation, grinding, carbonatization treatment, or other forms to reduce the size stability problem caused by free CaO/MgO elements and enhance its application suitability in various fields such as buildings, absorbents, catalysts (Gao et al., 2023; Ji et al., 2022; Yuan et al., 2024). Metallurgical slag has also played an important role in some other applications besides cementitious materials, road building, wastewater treatment, CO<sub>2</sub> mineralization and carbon capture; precious metals have also been extracted. Among them, the carbonation of steel slag can not only enhance its volume stability and material properties but also provide carbon sequestration capabilities, while metallurgical slag has been applied in advanced oxidation catalysis or adsorption for demonstrating "using waste to treat waste" (Qin et al., 2024; Yuan et al., 2024). Non-ferrous metal slag, for example, ferronickel slag, can also serve as a supplementary cementitious material or fine aggregate in building materials; Copper smelting slag and iron-bearing smelting slag contain valuable components such as Fe, Cu and Zn that have high recoverability through physical separation, hydrometallurgical leaching, etc., or selective recovery. In addition, Ti-containing slag from high-temperature furnaces has a titanium oxide content of around 18%-25%, an annual newly formed quantity of approximately  $3 \times 10^7$  tonnes, and the total stockpile is greater than  $8 \times 10^8$  tonnes. Therefore, the development directions for the titanium-resource-extraction-and-all-round-utilisation have been particularly significant (J. Liu et al., 2025; Qin et al., 2024; Yanning et al., 2024; Zhang et al., 2025).

### **Treatment and utilization of gypsum**

Mainly include flue gas desulfurisation gypsum (FGDG), phosphogypsum and waste gypsum from the construction of buildings. Industrial by-products of gypsum are mainly composed of calcium sulphate, and they usually contain some substances such as salts, acids or alkalis, lead, cadmium, mercury and other heavy metals and radioactive material (Liu et al., 2021; Maiti et al., 2023; Xie et al., 2024). In 2020, the world's total output of flue-gas desulfurisation gypsum was around 255 million tonnes; Among them, Asia made up roughly 55% of this figure and our country produced more than one hundred million tonnes each year. At present, phosphogypsum is generally used as the by-product from phosphorus industry for every 1 t of phosphoric acid produced about 3-5t Phosphorous waste. The annual world increase of phosphogypsum is approximately 300 million tonnes, and its total stockpile volume exceeds 600 million tonne (Liu et al., 2021; Maiti et al., 2023; Yang et al., 2023; Zhang et al., 2024).

Due to the higher degree of purification, flue-gas-desulphurisation gypsum has been more maturely applied to building materials and saline-alkali land reclamation; However, phosphogypsum has demonstrated a stronger potential for widespread application in cementitious materials, road construction, and mineral carbonisation technology-based carbon dioxide absorption applications. However, its long-term safety use still relies on controlling the leaching of soluble phosphorus, fluoride, heavy metals and radon (Maiti et al., 2023; Rashad, 2017; Zhang et al., 2024). Waste gypsum can also be utilised for mineralisation via carbonation. It has been revealed through relevant studies that the CaO content of flue-gas desulphurisation gypsum is around 25.27%-53.40%; and for phosphogypsum, it ranges from 30.50%-39.06%. Direct mineral carbonisation can achieve a conversion rate of up to 96%; thus, it seems likely that gypsum-derived solid waste would be feasible for sequestering CO<sub>2</sub> and producing valuable carbonate products (Kang et al., 2022). Gypsum may be used to form part of quarry backfill or mine-reclamation reclamation material at the same time. By combining clays, stones, sand powders, and other minerals with it to enhance the compaction degree and strength of backfill soil (Dang et al., 2013; de Rezende et al., 2017).

### **Treatment and utilization of red mud**

Red mud is strongly alkaline and solid residue that forms in the Bayer process of alumina production from bauxite. Usually, approximately 0.8-1.5 tons of red mud can be produced from 1 tonne of alumina. The world's annual production of red mud is around 140 million tonnes, but the proportion in use is relatively small so far.

Originally anticipated between about 2% and 3%, however, later studies have shown that the degree of acceptance is still quite low below 15%. Therefore, the main disposal mode is still large-scale stockpiling at present (Jia et al., 2024; G. Li et al., 2024; Pan et al., 2023; Raj et al., 2024). The main problem with treating red mud is its strong alkalinity and complexity of the chemical composition. The pH values are generally in the range of 10.0 to 12.5; Often there is an excess of salinity, sodium or other environment pollutants such as some heavy metals. If left uncontrolled, it may trigger land reclamation difficulties, dust storms, water source contamination problems as well as harm to plant development (Gräfe et al., 2011; Jia et al., 2024; G. Li et al., 2024; Mayes et al., 2016; Pan et al., 2023; Raj et al., 2024).

Safe disposal of red mud is unlikely to achieve it solely through one approach. Instead, usually a combination of methods is required, including neutralisation, washing with dilute hydrochloric acid or sodium chloride solutions, gypsum modification treatment and organic-microbial synergistic regulatory technology application; This can effectively transform the carbon dioxide absorption rate of contaminated soil to around 18 t/(hm<sup>2</sup>•a), which has an extremely low cost compared to other forms (Gräfe et al., 2011; Jia et al., 2024; Mayes et al., 2016). Regarding the utilisation of resources, red mud contains high amounts of Fe, Al, Ti, Na, V, Sc and rare earth elements; thus, it is considered to be a significant secondary resource. Major recoveries include physical separation, hydrometallurgy, pyrometallurgy, bio-leaching and electrodialysis, among which the recovery rate of valuable metals by some hydrometallurgical processes can reach above 99% to demonstrate relatively strong metallic recovery prospects (Jia et al., 2024; G. Li et al., 2024). Also, because the red mud resource is widely distributed throughout China with plentiful reserves, research has been conducted in multiple industries more extensively than in any other field. A few scholars have suggested that using red mud for the production of construction materials could enable a widespread implementation scenario of this waste material (Kumar et al., 2021; Raj et al., 2024). Jia et al. (2024) even mentioned that the high-strength performance of its red mud was as good as 129.5MPa and had considerable prospects for value enhancement in use after being converted into building materials.

## CONCLUSION

Broad prospects exist for utilising bulk industrial solid waste products containing fly ash, coal gangues, metallurgical slags, gypsum and red mud in the building material sector. Although their applications have been expanded to some extent due to technical, economic or management reasons. Generally speaking, the existing knowledge systems are centred around improvements in material properties and elucidations of the micro-mechanisms; Research on standards and regulations, industrial chains' co-ordination effects, regional distribution efficiencies, and policy instrument incentives has been less extensive. In the future, further study is needed into graded upgrading, multioriented integration, and green low-carbon processing technologies for industrial solid wastes; more attention should be paid to full-process supervision and industrialisation management at this time. Establish a systematic management system for raw materials, technologies, products and policies covering classification, evaluation, certification and support to promote an industry transformation where "industrial solid waste is usable" transforms into "sustainable scalable utilisation".

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